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A Real-Time, Space Borne Volcano Observatory to Support Decision Making During Eruptive Crises: European Volcano Observatory Space Services

Stephen Tait, Fabrizio Ferrucci
Institut de Physique du Globe de Paris
1 rue Jussieu, 75238 Paris cedex05, France
tait@ipgp.fr; ferrucci@ipgp.fr

Abstract— Within the Global Monitoring for Environment and Security (GMES) framework of the European Commission, the EVOSS consortium of academic and industrial partners has created a satellite-based volcano observatory, designed to provide the real-time information support to crisis management. Data from 8 satellite payloads acquired at 6 different down-link stations, are split and automatically processed at 5 locations (in Italy, the Netherlands, Belgium and Germany). The results are sent, in four separate data streams (thermal, volcanic SO₂, volcanic ash and - ground deformation), to a central system called VVO, the “Virtual Volcano Observatory”. The system operates 24H/24-7D/7 since October 2011 on all volcanoes in Europe, Africa, the Lesser Antilles, and the oceans around them, and during this interval has detected and monitored all eruptions that occurred in this region. EVOSS services are delivered to a group of 14 qualified users in Cabo Verde, Comoros, Congo, Djibouti, Ethiopia, France, Iceland, Montserrat, Tanzania, Uganda and United Kingdom. Physical modelling of eruptive phenomena, with an emphasis on rapid numerical calculations, underpins the satellite monitoring system.

Keywords: *Volcanic eruptions, Satellite monitoring, Fluid dynamic modelling, Decision Support System*

I. INTRODUCTION

Volcanic eruptions are a source of major natural risk to which a response strategy must be tailored. The environmental and humanitarian impact of a volcanic eruption always depends on two first order features: these are the eruptive flux and the overall amount of material ejected.

As is generally the case for major natural hazards, eruptions can occur on vastly different scales: the volume ejected in a given event is known to vary from several thousand cubic kilometers of magma (molten rock), to quite trivial fractions of one cubic kilometer ejected in small explosions. This variation of many orders of magnitude is accompanied by a frequency magnitude relationship, analogous to the Gutenberg-Richter law of global seismology, whereby the bigger the event, the longer the inter-event recurrence time. The current state of volcanology is that it is not possible to forecast the magnitude of an eruptive event, hence to decide a

monitoring and/or a crisis-management strategy, that by definition should be effective in realtime, must be flexible.

The eruptive flux, usually given as a mass rate (kg/s) or a volume rate (m³/s), can also vary strongly and plays a first order role in determining eruption dynamics, as discussed below (section IV). The underlying idea behind EVOSS is that it can provide back-up or even take over monitoring when the scale of an event starts to overwhelm resources on the ground. The emphasis is placed on satellite data acquisition with high temporal resolution, and on methods that enable eruptive flux to be determined in close to real-time.

This brief summary of the EVOSS system is broken down into three sections. First, we outline the key requirements of a volcano monitoring system based on various eruptive phenomena that can be expected. Second, we summarize the various satellite payloads used – in all cases launched for reasons other than volcanic monitoring – whose data streams have been adapted to our purpose. Third, we discuss the physical phenomena involved and explain how the interpretation of the satellite data is underpinned by mathematical models of those phenomena.

II. MONITORING NEEDS FOR VOLCANIC ERUPTIONS

Wherever volcanic risk is particularly high, and/or a country affected is advanced from the point of view of science and engineering, often a dedicated volcano observatory exists on the ground. However, the stark reality is that (notably in developing countries) the vast majority of dangerous volcanoes are very weakly monitored or not monitored at all on ground. In some cases, very long repose times can mean that little or no historical activity has occurred to guide expectations. It would not be financially realistic to imagine a major expansion of ground monitoring to achieve global coverage and hence a different strategy is required. Typically one does not know where the next volcano to go active will be located. Furthermore, even where advanced observatories do exist, they can still be overwhelmed by unexpectedly powerful events.

The fact that volcanoes can constitute an international, continental or even global-scale threat, and that, in the case of major events, ground-based monitoring infrastructure can be damaged or overwhelmed, makes a strong case for the development of a space-based strategy. One also has to allow for the fact that volcanic crises can be long lasting, from weeks to months, or even years, and that in a large monitored area, more than one volcano may be active at the same time. This amounts to a strong case for implementing an automatic observing system which can operate continuously without relying on human operators, but which can be easily supervised.

One also requires that the information can be delivered to the relevant trained users wherever they may be. A great advantage of a satellite-based observing system is that it is invulnerable to damage due to the eruptive phenomena. A final consideration is that the system be economically sustainable, i.e. that the data are not too costly to acquire, especially as large areas must be covered and long time series may often be required.

The EVOSS system has been designed with the above considerations in mind. It favours high temporal resolution of data acquisition, and uses data from weather satellites or from payloads on research missions which can be obtained free of charge. None of the satellite payloads used were originally conceived to study or monitor volcanoes, however, methods and algorithms have been developed so that the data acquired can be used for those purposes.

III. SATELLITE PAYLOADS

Data from 8 satellite payloads (SEVIRI, MODIS, JAMI, GOME-2, IASI, OMI, COSMO-SkyMed and, until April 8th 2012, SCHIAMACHY) acquired at 6 different down-link stations, are split and automatically processed at 5 locations in Italy, the Netherlands, Belgium and Germany). The results are sent, in four separate data streams (thermal, volcanic SO₂, volcanic ash, ground deformation), to a central system called VVO, the "Virtual Volcano Observatory". We focus here only on payloads that are used to determine eruption fluxes in near to real-time, and do not describe radar payloads, which work in delayed time and are used to mirror the actual, high-resolution topography after a major eruption has occurred at any volcano in any of the volcanic regions dealt with.

Thermal data from the SEVIRI instrument on board the geostationary meteorological satellites MSG (Meteosat Second Generation, of the European consortium for spaceborne meteorology EUMETSAT) are acquired over the whole visible disk (Figure 1) every 15 minutes. This disk defines the region of interest on which EVOSS has been tested and is being operated at the time of writing. The system thus covers all volcanoes in continental Africa, Europe and the Caribbean, as well as

those in the Atlantic Ocean and the Indian Ocean close to the east coast Africa.

SEVIRI pixels are large compared with volcanic edifices, hence subpixel resolution techniques [1] are used to extract information on the high-temperature features. Sufficient examples have now been accumulated such that comparison for the same events with the polar orbiting MODIS payload - which has higher (more than tenfold) spatial resolution and much lower temporal resolution (4 revisits daily, against 96 for SEVIRI),- that the results from SEVIRI can now be regarded as well validated [2]. This intersatellite comparison is indeed an important part of the validation strategy. Hot spots are automatically detected in real-time and their radiant power monitored.

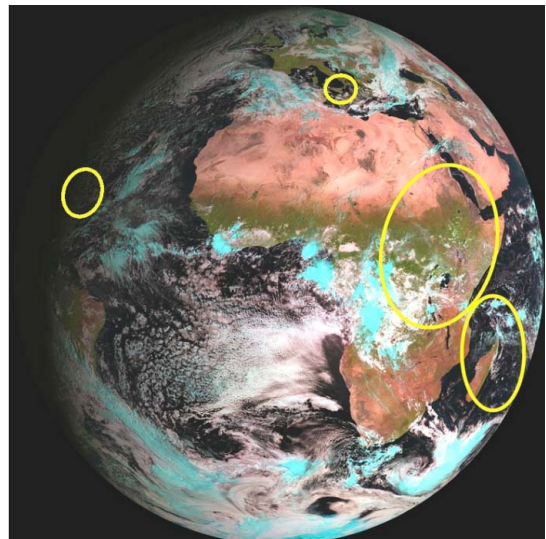


Figure 1 - The Earth disk seen by the SEVIRI payload on-board MSG-2 (Meteosat Second Generation, geostationary platform #2, currently orbiting at lat/long 0°). The main volcanic regions hosting eruptive activity in the last decade are outlined in yellow, ranging from the Lesser Antilles in the west, Iceland in the north, the volcanic provinces of central-eastern Africa and the volcanic islands of Indian Ocean (Comoros, Reunion) to the east. Iceland and its eighteen active volcanoes, are located at the upper northern limit for geostationary operations.

EVOSS also incorporates data from several payloads on polar orbiting satellites which can be used to measure concentrations of volcanic SO₂ and aerosols. These instruments visit a given site typically once a day so that the frequency of measurements does not approach that of SEVIRI. Nevertheless, by taking these several satellites together, EVOSS obtains several data per day for any given location. These include instruments measuring both in the infrared (IASI, onboard the polar orbiting platforms METOP-A and -B) and ultraviolet (OMI onboard AURA, and GOME-2 onboard METOP-A and -B).

More details of the sensitivities and methods employed can be obtained from [3] and references therein.

Figure 2 shows one example of data acquired within the framework of the EVOSS project on an eruption that took place at Nabro volcano in Eritrea. This volcano had no known historical eruptions and, being completely unmonitored on the ground, provides a good example of how the satellite volcano observatory can cope with a large event occurring in an unexpected place, but nevertheless having impact well beyond the borders of the country in which the volcano is located.

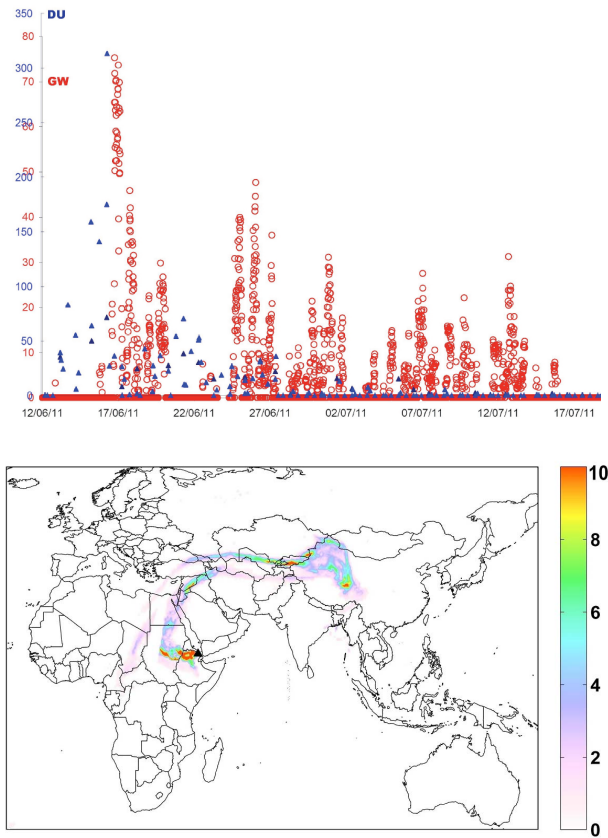


Figure 2 – Because of the lack of permanent volcano observatories in East Africa, the only known, large, historical eruption of Nabro volcano in Eritrea (June 11th to July 17th 2010), was detected and monitored only from space. Top: the thermal and SO₂ time series from the eruption. Red circles show the measured radiant heat flux in Watts (B. Hirn and F. Ferrucci, unpublished). Blue triangles show the maximum sulfur dioxide column measured in Dobson Units, i.e. mass /unit area. Bottom: after one week of eruption the SO₂ concentrations in the eruptive cloud, advected from east Africa across Asia by strong winds, could still be detected and measured [3], [4].

The time-series graph of Figure 2-top shows that very intense thermal radiance occurred early in the eruption, reaching an exceptional 80 GW, and that this was accompanied by a very strong peak in sulfur dioxide degassing. Indeed a truly remarkable amount of sulfur dioxide was released in this event: the plume reached the lower stratosphere and was advected in a few days as far as China – see Figure 2, bottom. The lava flow that

formed in this eruption was not visible during the first few days because of very thick clouds, and when first seen was already close to 20 km. in length. The sulfur dioxide was released predominantly during an early phase of intense degassing, whereas the high thermal radiance was maintained over a longer period.

This example is important to emphasize the great variability in intensity (related to flux) and magnitude (related to overall mass or volume released) that is possible during a volcanic eruption, in particular if its magnitude is significant – as currently observed when activity resumes after long periods of dormancy. However, such data sequences must be interpreted in terms of specific eruption dynamics which requires a close collaboration between scientists with remote sensing expertise and those with volcanologic expertise, particularly in the field of eruption dynamics (section IV).

IV. PHYSICAL MODELLING OF ERUPTIVE PHENOMENA

The interpretation of the satellite data is not straightforward because of the variability of the volcanic phenomena involved. The concept of eruption regimes is useful, in which characteristic physical phenomena take place, albeit of variable magnitude. Key examples of these dynamic regimes are i) lava flows, ii) fire-fountains and iii) “Plinian” eruption columns.

In the first and simplest, a hot viscous gravity current flows on the topography of the volcano.

In the second, droplets of magma are projected several hundred meters to ~1 kilometer above the vent by a strong gas jet, after which many fall back to the ground around the vent to feed lava flows, though the smallest particles are carried up further by the hot gas. Lava flows and fire-fountains commonly co-exist, particularly in early stages of eruptions.

In the third, small ash particles are injected several to tens of kilometers into the atmosphere by a very strong turbulent jet of gas. These eruptive phenomena can be modeled, but here one must find the right balance between including sufficient complexity of the natural systems and efficiency of numerical calculations.

The physical models developed for these volcanic flows have reached different levels of sophistication or maturity. Taking the example of Plinian eruption columns, one- two- and three-dimensional now do exist. The most recent versions of the latter have achieved some measure of success in simulating the natural phenomena, e.g. [5], but suffer from the fact that they are computationally expensive, and these models cannot be run quickly with current resources.

At the other end of the spectrum, the one-dimensional models use the formalism of entrainment to describe the key phenomenon of turbulent mixing between the ash-

laden jet and the atmospheric air, e.g. [6]. Despite their relative simplicity, the most recent versions of such models give useful and quite accurate results and the corresponding numerical codes run sufficiently fast that the modeling can, in principle, be done in real-time. Rapidity and robustness are important if physical models are to be used to evaluate rapidly the behavior of a given event, as it is happening.

Fluid dynamic simulations of eruptive phenomena are typically done as “forward models”, with the flow being observed as the result of the specified initial and boundary conditions. The rate of magma eruption during any given event, which is always a key factor in determining how the flow will behave is required as input for a model. This is, however, notoriously difficult to measure in real-time by means of ground observations, partly because of the inherent danger of the phenomena involved, and partly because the precise site of an eruptive vent is unknown at best until a very short time before eruption commences.

Hence it is a practical impossibility to position the necessary instruments ahead of time. Satellite remote sensing, using the thermal power emitted, provides the potential to solve this problem and measure eruptive mass flux: however, fluid dynamic models must be used to convert the observables into quantitative data, because qualitatively different eruptive styles and eruption regimes occur. In other words, satellite data interpretation must be backed up by models which in turn require satellite data for their input conditions. Hence, one must find a way to integrate the two into a consistent methodology. This is not yet achieved in terms of an operational system, and in current practice models are used offline to search for a “best” interpretation of the data.

Below, we only summarize the main features of the models and do not give quantitative details, for which the interested reader is referred to more complete treatments in each case.

A. Radiant flux from lava flows

The radiant power emitted by a lava flow depends primarily on its surface temperature. This temperature varies from approximately 800 – 1250 °C depending on the chemical composition of the lava (relatively rare lava types with a predominantly carbonate composition, as opposed to the common silicate types, also exist with exceptionally low eruption temperatures of ~500 °C). Following early attempts to assess the potential of thermal remote sensing to obtain information on lava eruptions, e.g. [7,8] over a number of years, remote sensing data have been interpreted in terms of a model that does not incorporate fluid dynamics. The lava flow was effectively treated as a static radiating “hot-plate” of fixed area in which a steady balance of heat supply from below and loss from above had become established. [9] took one step

forward to include flow processes, looking at the latter, relatively simple case of a hot iso-viscous gravity current, losing heat from its upper surface as it flows.

Heat loss is predominantly controlled by radiation, but also by some convection in the atmosphere. More sophisticated flow models have been published including more complex lava rheology, and this is a very important feature, however, these models were mostly intended to look at lava flow morphology, eg. [10], or took isothermal conditions for the upper surface, eg. [11] and did not calculate the radiant flux that is required to support remote sensing applications.

In [9], it was shown that when the lava flux at the volcanic vent is held constant a steady thermal state becomes established, in which cooling at the surface by radiation and convection in the air balances the advection of heat within the flow, after an initial transient state whose duration depends on the liquid viscosity. In this model framework, the lava mass flux at the vent, which is a key measurement required to assess an eruption, can therefore be deduced from the satellite data of radiant flux, however, a number of simplifications inherent in this model do need to be addressed before a more reliable quantitative interpretation of the satellite data can be made in terms of lava effusion rate.

First, lava flow rate is unlikely to be constant during an eruption, and only further analysis can determine how much transient information might be derived. Nevertheless a steady model can be relevant if the time-scale on which the thermal steady state is established is short with respect to that over which eruption flux varies. Second, natural lavas cool strongly as they flow and undergo large rheological changes because they crystallize and melt viscosity is a strong function of temperature [11], and this complicates the temperature structure of the surface with respect to that of an iso-viscous fluid. In simple terms, part of the surface develops a crust as it cools and stops moving, whereas the hottest, freshest part of the lava flow is still close to eruption temperature and still moving. The overall thermal signal seen by a satellite payload such as SEVIRI therefore integrates the radiation coming from both parts of the flow [2].

B. Volcanic gas emissions during lava eruption

All naturally occurring magmas contain volatile species dissolved in the silicate melt, and these exsolve as bubbles as the magma rises to the surface and decompresses. Although volatiles are present in minor quantities in terms of mass (typically one to a few weight percent), because of the very large differences in the compressibility of gas and melt, the gases represent a very large volume fraction at the eruption site. Indeed it is the expansion of the gas phase that causes the violence of volcanic eruptions and drives strong eruption jets.

Although the most abundant magmatic gas is water vapor, other species are present, and some of these are at sufficiently low concentrations in the earth's atmosphere that their emission by volcanoes can easily be detected.

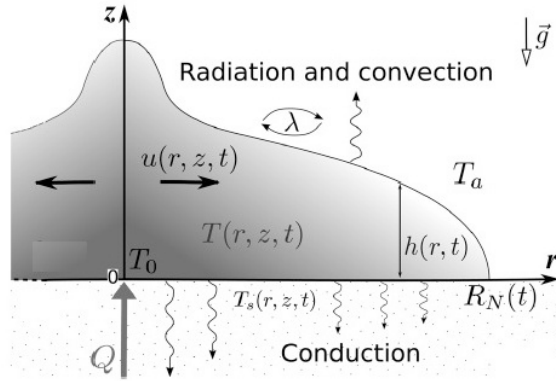


Figure 3. Shows schematically the heat budget for a lava flow: the key feature for present purposes are the thermal boundary conditions at the upper surface where heat is lost by radiation and convection, balancing the advection in the flow.

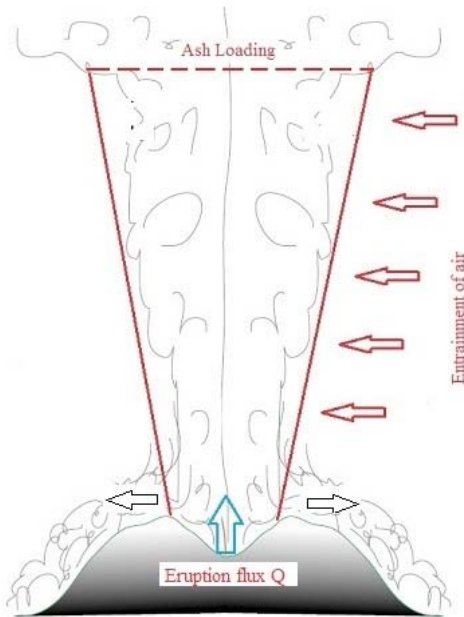


Figure 4. A sketch of an explosive column into which air is entrained by turbulent mixing at the margins. The total amount of air mixed in relative to the eruption flux determines the ash loading at the top of the column. Three-dimensional calculations are required to represent the turbulent flows involved [5].

A notable example is sulfur, which is typically emitted by volcanoes in the oxidized state as sulfur dioxide. When the viscosity of the liquid magma phase is relatively low (on the order of $10 - 1000 \text{ Pa s}$), the phenomenon of separated flow can occur in the conduit, which means in practice that large gas slugs formed by

the coalescence of bubbles which rise much faster than the melt [12].

At the vent, the gas expels droplets of liquid producing a dynamic structure known as a “fire-fountain”. Many of the coarser droplets fall out of the gas jet, piling up around the vent, often still hot enough to re-coalesce and feed a lava flow. The finer droplets are carried higher and drift away with the plume as small ash particles. Fire fountaining therefore produces an intense release of volcanic gas into the atmosphere, often associated with a strong lava flow on the ground, depending on the mass flux of the eruption. In terms of the satellite data, we can expect to see a strong sulfur dioxide signal, if the magma indeed contains a reasonable concentration of this gas, as well as a very strong thermal signal. These characteristics can be seen in the example shown in Figure 2.

C. Explosive eruption columns and atmospheric ash loading

In the fully explosive eruption regime, the magma undergoes fragmentation whilst rising in the eruption conduit and the mixture that exits from the vent at the Earth's surface is a fully turbulent gas jet laden with small particles. In short the gas volume fraction becomes so large that the gas phase becomes the continuous phase (whereas deep in the conduit the liquid magma phase was continuous, containing dispersed bubbles).

From a fluid dynamic point of view, this mixture is typically handled as a dusty gas, i.e. a gas whose thermodynamic properties are affected by the presence of small particles but with negligible viscosity.

Over a number of years, numerical codes have been developed, the most recent versions of which carry out fully three dimensional calculations to represent the turbulent flows involved [4]. A review of this large literature is impractical here. For present purposes, an important approach has been to adopt the mathematically simpler approach, introduced for other applications in the pioneering paper of [13] in which turbulent mixing between eruption jet and atmosphere is described using an entrainment coefficient [14,15,16]. A review of this large literature describing the application of fluid dynamics to volcanic flows is impractical here - see above references, as well as the review of [6].

In [16], the dependence of the entrainment coefficient on the buoyancy of the jet (or plume) is introduced, whereas previously it was taken to be constant. This is considered an important innovation in that volcanic jets undergo a very large change in their buoyancy relative to the atmosphere as they rise.

The jet expelled at the vent is denser than the atmosphere and rises under its own momentum whilst strongly decelerating. The entrained air is strongly heated

by efficient thermal exchange with the tiny hot particles and rapidly expands.

This process often (but not always) leads to a density inversion in which the bulk jet density becomes less than that of the atmosphere and the column then rises as a buoyant plume until it reaches a height of neutral buoyancy in the stratified atmosphere and starts to spread horizontally. This is the major process by which large amounts of ash can be injected into the atmosphere at elevations of several to several tens of kilometers. Transport and dispersion of ash and gases by strong stratospheric winds to large distances (Figure 2), and persistence of ash in high concentrations in the upper troposphere and the tropopause, pose a major threat to air navigation.

The models cited above show that the major controls on the height reached by the eruption column are the mass flux at the vent, the stratification of the atmosphere and the amount of turbulent mixing as represented by the entrainment coefficient. When the momentum of the eruption jet is insufficient to reach the point of density inversion, the column partially collapses to produce hot, turbulent and rapidly moving gravity currents on the topography of the volcano.

This category of flows, collectively known as “pyroclastic”, is quite complex to handle from a dynamical standpoint as the threshold of collapse is relatively well understood [17,18], but the quantitative behavior of flows fed from a collapsing column is still the subject of much active research at the time of writing.

V. PERSPECTIVES FOR VOLCANIC CRISIS MANAGEMENT AND DECISION SUPPORT

Since March 2012 the EVOSS system is fully operational from the remote sensing standpoint, meaning that the data processing and real-time delivery of dynamic products (such as fluxes and loadings from erupted lavas, sulfur dioxide and ash) to central servers for dissemination, are automated.

Currently, the dynamic models sketched briefly in the previous section can already help translating real-time observed quantities – which are the core of the system – into offline quantitative interpretations. The latter, constitute the perspective evolution of EVOSS, to better assist in volcano monitoring and prediction with a multi-disciplinary blend of simultaneous observations.

This perspective target could be achieved in a number of automated ways, for example, (i) using Automated Neural Networks as a real-time, non-linear interpolator acting on pre-computed straightforward modelling of thermal, gas, ash and ground deformation anomalies [19], or (ii) exploiting Web semantics and stream reasoning

methods with advanced Complex Event Processing techniques [20].

Still looking to the future, it is possible to anticipate an expansion of the EVOSS system from its current region of interest to the global scale, exploiting in near-realtime the multispectral payloads on board the geostationary platforms MTSAT-1 and -2 (orbiting at 145°E) and GOES-East. Indeed, the architecture of the system is such that as data streams from new satellites and the algorithms developed to generate appropriate products come on-line, these can be “slotted into” the system. In this way the system can maintain its state-of-the-art character from the remote-sensing point of view, and remain flexible from the point of view of downstream applications for crisis management.

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